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Design of a Bipropellant Catalytic Ignition Torch for a Biliquid HTP/Fuel Thruster

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Abstract
The sizing, design, conception, implementation and experimental testing of a catalytic bipropellant ignition torch is tackled in this paper. The goal is to allow the ignition of a non-hypergolic biliquid spray of 98 % HTP and a hydrocarbon fuel in the PERGOLA facility, without any additional propellant tank dedicated to feeding the ignition device. A deviated portion of the propellants is used to produce burned gases ejected on the biliquid spray in the combustion chamber, through staged-combustion. Upstream of the biliquid spray, burned gases are generated through the self-ignition of the liquid fuel caused by the hot oxidizing steam released subsequently to the catalytic decomposition of 98 % HTP.

1. Introduction

In the combustion chamber of a storable biliquid propellant thruster, ignition can be either hypergolic, or ensured by an external source [1]. An external ignition system provides a sufficient local energy input to ignite the propellants and achieve stable combustion. Such systems require additional components (extra tank, high-voltage electronics to generate a spark, etc.), which increases the mass and complexity of the thruster. Research has focused on a sustainable and promising green storable propellant, hydrogen peroxide, in the efforts of supporting a greener space propulsion. Highly concentrated hydrogen peroxide in aqueous solutions (High-Test Peroxide, HTP), mixed with a few stabilizing agents, has been studied, developed and used as a propellant in space propulsion [2], [3]. HTP can be used as a storable oxidizer for ignition of kerosene or a hydrocarbon in a biliquid bipropellant thruster, assisted by an ignition system such as a torch [1]. However, various HTP applications in propulsion benefit from the ability of hydrogen peroxide to spontaneously decompose into water vapor and molecular oxygen in a highly exothermic disproportionation reaction. In monopropellant engines, designed for orbital manoeuvres or attitude control systems, thrust is generated by the expansion of hydrogen peroxide catalytically decomposed gases [4], [5], [6], [7]. Furthermore, the oxidizing properties of the hot catalytically decomposed gases of HTP in the higher concentration ranges can also be used to promote fuel self-ignition [8], [9]. This latter phenomenon can be further referenced as “staged-combustion”.

Previous experiments carried out in the high-modularity, low-mass flow rates and low-pressure thruster-like facility “ACSEL” [10], led to the successful ignition of a liquid decane or dodecane jet by the high temperature gaseous stream of decomposed hydrogen peroxide, in the presence of a Pt catalyst developed in-house. Injection topology, mixing, atomization, ignition, combustion stability and performance of the liquid fuel jet in a reactive, high-velocity, hot oxidizing both in crossflow and coflow configurations were investigated in an optical chamber. On the other hand, the facility “PERGOLA”, a bigger scale thruster-like experimental bench dedicated to the study of biliquid storable propellant combustion, enables to focus on the ignition issue in non-hypergolic bipropellant combustion [11]. The combustion of HTP and hydrocarbons or alcohol was successfully ignited by the means of a H2/air ignition torch, and combustion was characterized in this facility. For space propulsion applications, implementing an ignition system that does not require any additional tank would reduce the embarked mass. The use of a small scale staged-combustion as an ignition torch using propellants derived from the main tanks is thus investigated.

Various catalytic staged ignition systems using HTP have been developed. A monopropellant system, in particular [12], was implemented for the ignition of a fuel-rich LOX/LH_2 or LOX/kerosene mixture. The ignition process in this torch prototype relied solely on the high-temperature oxygen generated from HTP decomposition, which was hot enough to exceed the autoignition temperature of the fuel while remaining low enough to eliminate the need for an active cooling system. The manufactured torch, using a catalyst composed of stacked silver grids and having the

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same footprint as the Vinci ignition system, was successfully reignited 15 times for a calculated nominal power of 100 kW. However, earlier research conducted by the same team [13] concluded that decomposed HTP gases heat alone was insufficient to ensure ignition. As a consequence, only bipropellant combustion heat could provide the necessary energy to ignite a non-hypergolic bipropellant mixture. Indeed, an initial version of a monopropellant catalytic torch failed to ignite gaseous hydrogen in a test setup due to an insufficient exit temperature [13]. To increase the flame temperature and achieve rocket engine ignition, a bipropellant igniter was designed, manufactured, and tested using liquid ethanol. This system also employed silver grids with a loading rate of 6 g/min/cm². A later version, adapted to GCH_4 or GH_2, is expected to enable the ignition of a lower stage LOX-LH_2 or LOX-LCH_4 engine.

The objective in this paper is to develop, test and implement such an ignition system. Specifically, a bipropellant catalytic torch is designed based on this process, and adapted to the ignition of the combustion facility PERGOLA, using the same propellants (HTP/dodecane) as the main combustion chamber.

2. PERGOLA experimental facility

Storable propellants atomization, ignition, combustion stability and propulsion efficiency are studied in a facility named “PERGOLA”, developed through collaboration research activities between PPrime institute and CNES [11]. This thruster-like bench has been designed with high modularity, allowing physical and optical diagnostics in a pressurized combustor featuring relevant flow conditions. Cross-section and full Computer-Assisted-Design visualizations of PERGOLA and its injector are presented in Fig. 1. This facility allows to reach a propulsive thrust up to 1 kN, and a combustion pressure up to 5 MPa for a propellant flowrate of a few hundred g/s during up to 1 min. The bench has a modular conception composed of an injection module, a combustion chamber and an exit nozzle. The original torch ignitor fed with air and dihydrogen (see Fig. 1) was replaced by a new staged-ignition torch fed with the same propellants as the injector (HTP and dodecane).

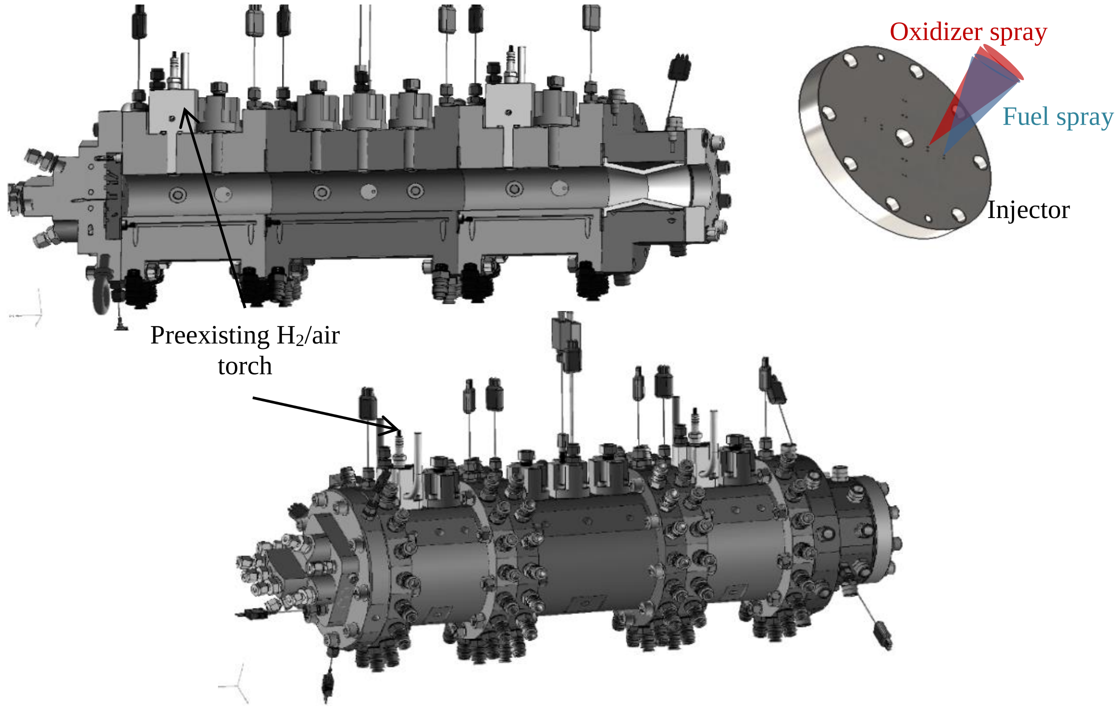

Fig. 1: Experimental facility PERGOLA

In this study, tests are carried out with a cylindrical 350 mm-long opaque combustion chamber and a biliquid injection system composed of 4 like-doublets per propellant, placed circumferentially on the injector plate. All parts of the combustor are water-cooled to allow a good control of the initial conditions. The exit throat is chosen to render a combustion chamber characteristic length of 4.4 m. Even though a diverging nozzle is used in this study to enable the computation of a thrust coefficient (c_F), the focus here is rather on ignition capabilities and on the combustion performance (c^*), and not primarily on the propulsive performance optimization, as tests are performed at sea level. The facility allows the recording of the combustion pressure and propellants pressure *via* piezoresistive sensors (GE UNIK5000, 0.1 The propellants mass flow rates are measured by Coriolis sensors (Rheonik RHM, 0.5 %).

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3. Design of a staged-ignition torch

3.1 Sizing & integration

The proposed design of catalytic ignition device replacing the H_2/air torch requires the deviation of a portion of both propellants (HTP and fuel) mass flow rates from the main feedlines. From the torch feedlines, HTP is decomposed by a catalytic bed inside the torch. The fuel (dodecane) is then injected into the torch combustion chamber, leading to self-ignition [14]. The flow of resulting burned gases is then ejected directly into PERGOLA's main chamber, in the wake of the HTP/dodecane bipropellant sprays supplied by the injector to induce ignition of the main flow. Such ignition device generates a local increase of temperature in the main combustion chamber, allowing the propellants to ignite. The fluid diagram of the system is illustrated Fig. 2.

The specifications of an igniter are based, among other factors, on the thermal power required to ignite the propellants, injected in liquid form into the combustion chamber. The thermal power is provided by the burned gases produced by the torch, as presented in Eq. (1). P_{torch} is intrinsically dependent on the chosen couple of propellants: on the mass flow rate of propellants burned inside the torch (oxidizer + fuel), $\dot{m}_{torch}$, and on Q_c, which is the heat of combustion reaction at the given equivalence ratio. To maximize the temperature of the combustion products from the torch, the stoichiometric mixture ratio is selected.

$$P_{torch} = \dot{m}_{torch} Q_c \tag{1}$$

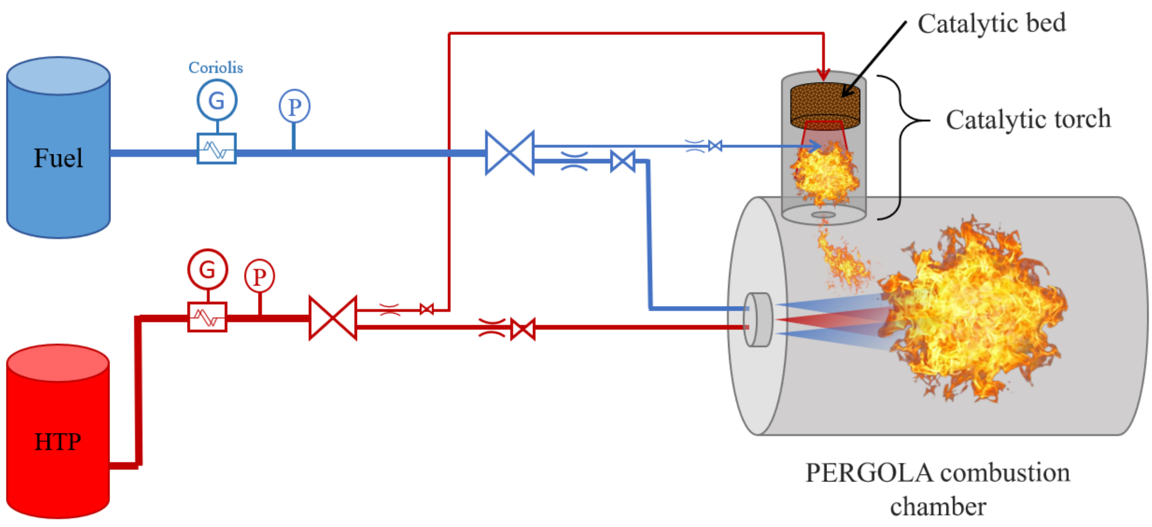

Fig. 2: Fluid diagram of the bipropellant catalytic igniter implemented in the biliquid fuel/HTP combustion facility

The selected performance requirements for the igniter design, adapted from the PERGOLA H_2/air torch and the catalytic chamber, are to achieve the same power output as with H_2/air torch, with an operating duration of several tens of seconds. Additionally, the torch exit geometry must be sized for insertion into the PERGOLA test section while complying with size constraints. To enable such an output, a fixed HTP flow rate $\dot{m}_{torch}$ of 15 g/s is chosen. The thermal power of catalytic decomposition $P_{torch_{monopropellant}}$ is 26 kW, whereas for the same $\dot{m}_{torch}$ and an equivalence ratio of 1.2, the power increase by a factor of 4.

3.2 Design of the proposed technical solution

The ignition torch device was designed to allow the study of HTP catalytic decomposition and its ability to sustain fuel combustion. This duality in possible studies enables the characterization of both catalytic decomposition and combustion in terms of performance characterization, catalytic reactivity, and test repeatability during the catalytic bed ageing, with repeatable tests.

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The igniter design consists of three parts: the HTP injector and catalytic decomposition chamber, the combustion chamber, within which fuel is injected transversally for a swirl mixing, and a 45° ejection throat. A given mass of catalyst is inserted into a removable cartridge. The catalyst is compressed within the cartridge before being inserted into the catalytic chamber of the torch, allowing repeatable packing and compaction of the catalytic bed. The targeted catalytic capacity of the catalytic bed is up to 1000 kg/m^3/s. The HTP flow rate is injected into the catalytic chamber through a calibrated orifice. The mass flow rate $\dot{m}_{torch}$, measured by a Coriolis mass flowmeter, is controlled by the calibrated orifice and regulated by a valve that allows for either pulsed injections or a continuous injection plateau. Table 1 presents the designed catalytic ignition torch characteristics.

Table 1: Specifications of the torch igniter

Propellants	**Oxidizer/fuel**	HTP 98%/Dodecane ($C_{12}H_{26}$)	
	Stoichiometric equivalence ratio	7.5	
Combustor	Combustor characteristic length	4.4	[m]
	Combustor total mass flow rate	150	[*g/s*]
Igniter	Igniter total mass flow rate	15	[*g/s*]
	Catalytic capacity	700–1000	[kg/m^3/s]
	Number of ignitions	> 5	
	Catalytic bed preheating	50–170	[°*C*]
	Torch volume	34	[*cm*^{3}]

The catalyst selected for this study is called CC-1-1100, and was prepared following the steps presented by Cottenot *et al*. in reference [15]. The catalyst decomposition activity, ensured by the use of a low-diameter spherical shape support (thus providing a large accessible surface area), combined with high catalytic resistance imposed by a high-temperature reduction (>1300 K), allows a practical use in an igniter requiring sufficient catalytic activity to initiate the decomposition of 98 % HTP, while enabling multiple ignitions.

To determine the pressure losses within the catalytic bed, the static pressure and temperature of the decomposed gases are recorded both upstream and downstream to the catalytic chamber, using K-type thermocouples (1 % uncertainty) and piezoresistive pressure sensors (GE UNIK5000, 40 bar, 0.2 %). The catalytic chamber is preheated *via* a heating collar placed around the catalytic chamber, and its temperature is regulated between 50 °C and 170 °C, monitored by a K-type thermocouple attached to the chamber wall. CAD cross-sectional view and photographs of the catalytic ignition torch are presented in Fig. 3.

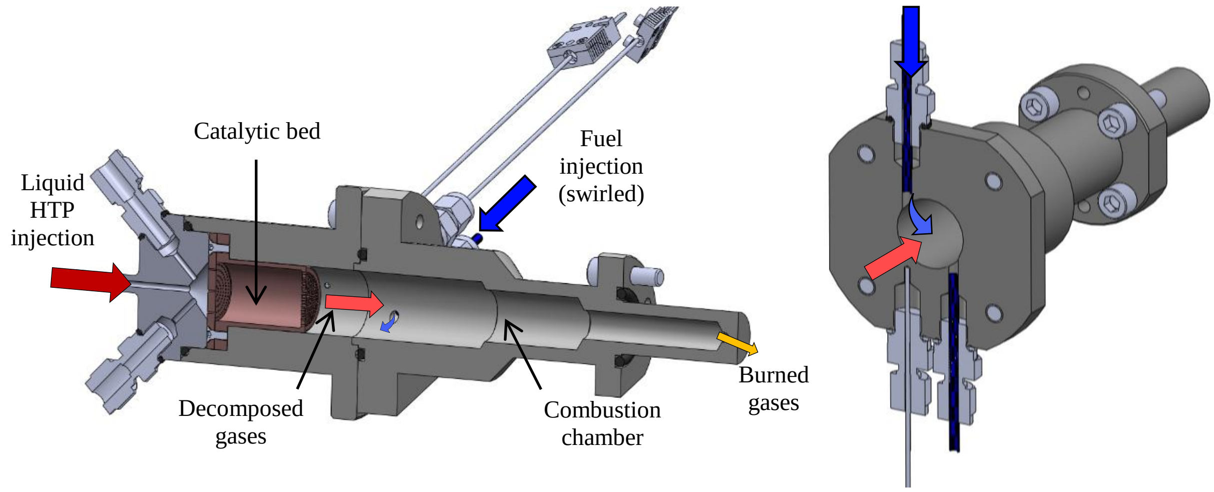

Fig. 3: Cross-section views of the catalytic igniter

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4. Experimental testing

4.1 Reception tests

Following the design and manufacturing of the catalytic ignition torch, preliminary ignition tests were conducted to characterize the torch's combustion feasibility and performance, with burned gases being ejected into ambient conditions. This reception study was crucial towards the assessment of the torch, as its opacity and few placed sensors offer little understanding of the fuel injection topology and the degree of confinement in the mixing zone between the decomposed gases and liquid fuel.

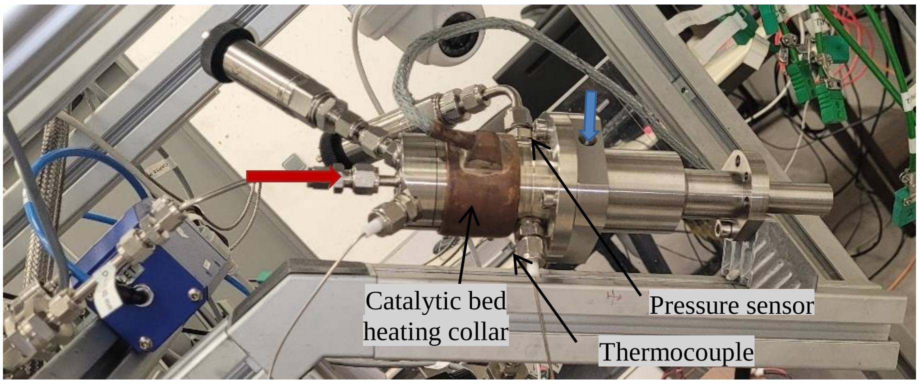

Fig. 4: Photograph of the catalytic ignition torch during reception tests

For these reception tests, a 10 s plateau is used with a 6 s delay between the beginning of oxidizer injection and fuel injection. The measured data (mass flow rates, temperature, and pressure) from a representative test carried out are presented Fig. 5. Data shows that the catalytic bed requires approximately 4 s of transient operation to transition from the initial catalytic bed temperature set (120 °C) to the nominal decomposition temperature (around 1000 °C). Not long after the dodecane started being injected (around 20 ms), ignition is visible and characterized by a rise in pressure, and stable combustion by a low fluctuation of the recorded pressure until the end of the fuel injection.

Due to the fluid supply constraints of the PERGOLA fluid system, several calibrated orifice diameters, which control the mass flow rates, upstream to both oxidizer and fuel were tested to achieve an equivalence ratio around 1, with the same feeding pressure for both propellants. Various tests were conducted with different injection pressures (P_{inj}) and calibrated orifice diameters (d_{ox} and d_f). Two examples of tests are presented in Table 2 which also summarizes the measured values of temperature, pressure, and flow rates, averaged over two seconds of steady-state combustion. Additionally, it presents the calculated values of power, characteristic velocity, and characteristic velocity efficiency. The test illustrated in Figure 5 is highlighted in Table 2. More than 15 tests were successfully performed, proving the high capability of the catalytic torch to operate.

Table 2: Summary of reception tests and averaged recorded and computed data in nominal conditions

d_{ox} / mm	d_f / mm	ER (-)	P_{inj} / MPa	$\dot{m}_{ox}$ / g/s	$\dot{m}_{fuel}$ (g/s)	P_{torch} / bar	T_{cata} / °C	$c*$ / m/s	η_{c^*} / -	P / kW
0.4	0.2	**1.03**	**1.99**	6.32	0.86	10.29	918	**1379**	0.868	**47**
0.6	0.2	**0.59**	**1.95**	9.17	0.72	14.68	905	**1446**	0.990	**46**
0.6	0.3	**1.24**	**2.93**	11.82	1.94	20.80	875	**1454**	0.900	**85**

The success of those reception tests proved that the torch achieved the desired power level, similar to that of the H_2/air torch currently used on PERGOLA, with sufficient efficiency (η_{c^*} = 90 %). All the tests resulted in successful ignition, making it possible to consider future large-scale tests in the facility to ignite the main circuit using the catalytic torch under selected operating conditions.

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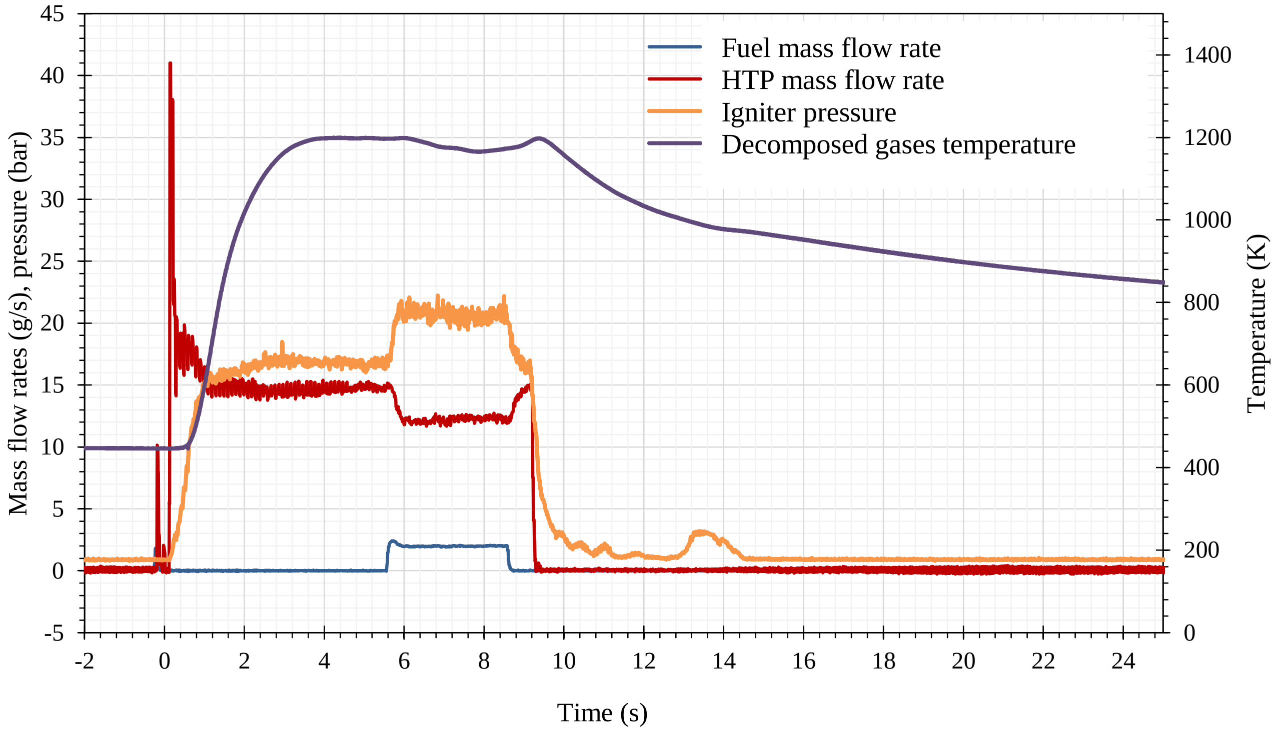

Fig. 5: Recorded data in the catalytic bipropellant igniter from a reference reception test

4.2 Ignition test of PERGOLA combustor

For each propellant, PERGOLA facility imposes the same feeding pressure for both the torch and the injector (see Fig. 2). The flow of each propellant is split in two downstream of the main valves, either towards the torch and the main combustor. The magnitude of each flow is proportional to the cross-section area of calibrated orifices, and can be switched on or off by the means of valves positioned downstream to the flow splitting. This allows an independent control of the 4 flowrates. For the torch propellants, the calibrated orifices of diameter 0.6 mm (oxidizer) and 0.3 mm (fuel) placed upstream of the torch, allow for a fuel-HTP equivalence ratio of approximately 1.25 across a range of feeding pressures. As for the main combustion chamber, the calibrated orifices located upstream of the injector are 1.0 mm (oxidizer) and 0.5 mm (fuel).

The test operation sequence is schematized in Fig. 6. The oxidizer is first injected in the torch during a few seconds to allow a rise in the catalytic bed temperature and ensure nominal catalytic decomposition of the HTP in the catalytic igniter. Following this time period, dedicated to catalytic bed activation, fuel is injected in the torch downstream of the catalytic bed, which results in the self-ignition of the propellants inside the torch. Then, the main circuit of both propellants is opened, which feeds the combustor through the injector doublets at low pressure (1.5 MPa). Both the torch and the main circuit are kept opened during a few seconds, after which the torch is disabled, and the feeding pressure is increased to reach a nominal feeding pressure of 8 MPa (oxidizer) and 4 MPa (fuel). These high-pressure nominal conditions are maintained during a steady plateau of 10 s. The torch is disabled during nominal stabilized combustion conditions, to perform measurements on the steady combustor operation, independently from the ignition device.

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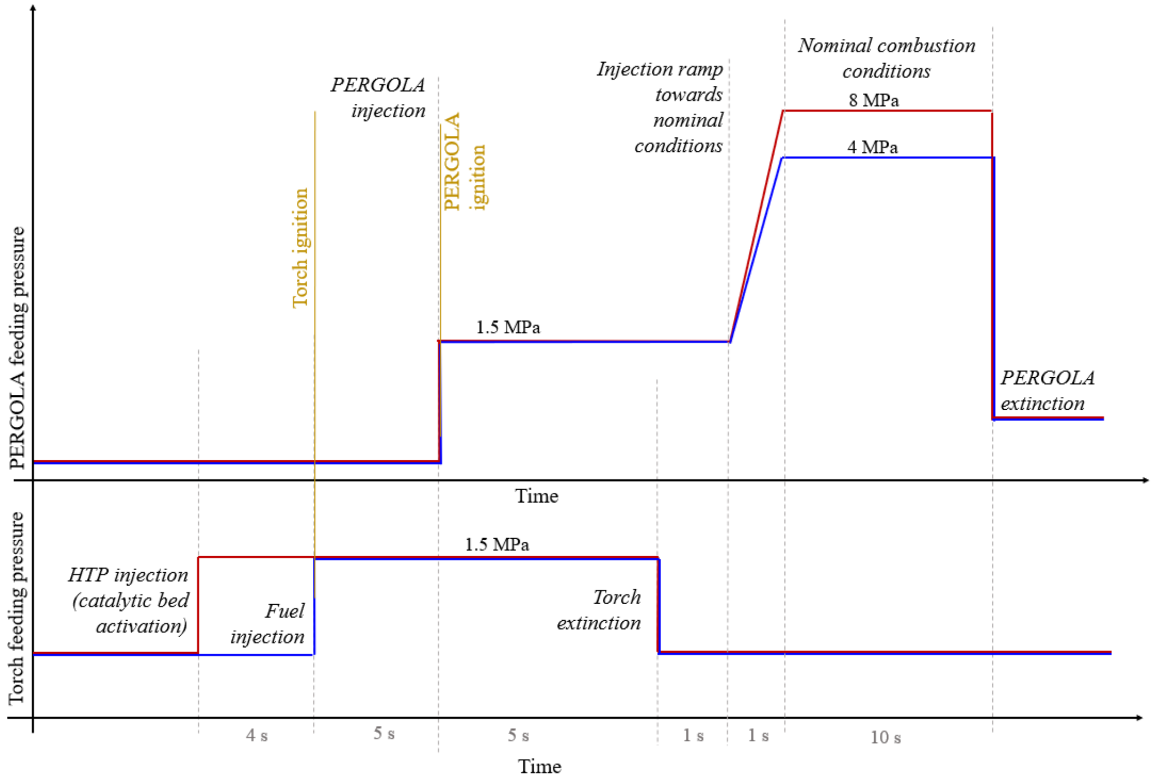

Fig. 6: Sequence of propellant injection during PERGOLA ignition tests with the bipropellant catalytic torch

The data recorded during a test conducted following the injection sequence illustrated in Fig. 6 is presented in Fig. 7. The values of the pressure measured in the torch and in the PERGOLA combustion chamber, as well as the total flow rates (torch and combustor together) for both propellants, are shown.

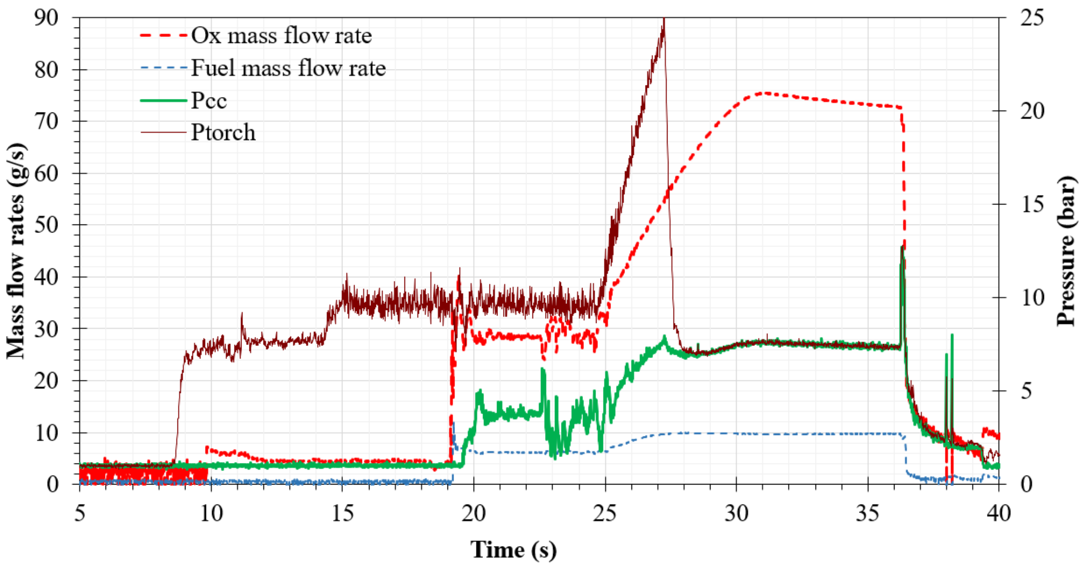

Fig. 7: Recorded data in the catalytic ignition torch and PERGOLA combustion chamber during an ignition feasibility test

The increase in torch pressure at t = 8 s and t = 14 s indicates the beginning of HTP and fuel injection, respectively (followed by the start of combustion at t = 15 s) in the torch. The injection of propellants into the PERGOLA combustion chamber begins at t = 19 s, followed by the ignition of the main combustion chamber at t = 20 s. The injection into the torch, and therefore the combustion in the torch, is cut off during the pressure (and thus injection mass flow rate) ramp-up at t = 27 s.

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Nominal conditions at maximum pressure and flow rates are established from t = 31 s to t = 36 s, at which point the injection is stopped. During this plateau, a characteristic velocity close to 1400 m/s is calculated, indicating efficient combustion in the water-cooled, copper-alloy combustion chamber.

5. Conclusion

A catalytic bipropellant ignition torch, intended for use in a bipropellant thruster and compatible with the PERGOLA test bench, have been designed, developed, and successfully validated, demonstrating a 100% success rate under all considered operating conditions. The torch relies on the self-ignition of a fuel (dodecane) directly injected into a flow of hot gases from the catalytic decomposition of 98% HTP. The optimal conditions for igniting the main combustor and a test sequence compatible with nominal, experimental conditions have been defined.

A successful test enabled the ignition of the PERGOLA combustion chamber by the catalytic torch, cancelling the need for an additional propellant tank solely dedicated to ignition. Following the torch ignition, the injection of propellants into the main combustor led to stable and efficient combustion (c^* = 1400 m/s). Further ignition tests at larger mass flow rates and combustion pressure, and longer duration, as well as optimizations of the catalytic bed and igniter design in terms of compacity are looked upon for future studies. Furthermore, a visualization in the combustion chamber during the biliquid spray injection and ignition by the torch ejected burned gases may help understand the complex phenomena at stake.

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